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SUPERCONDUCTING MAGNETS FOR MUON CAPTURE AND PHASE ROTATION

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ABSTRACT

There are two key systems that must operate efficiently, in order for a muon collider to be a viable option for high energy physics[1,2]. These systems are the muon production and collection system and the muon cooling system. Both systems require the use of high field superconducting solenoid magnets[3]. This paper describes the superconducting solenoid system used for the capture and phase rotation of the pions that are produced on a target in a high intensity proton beam.

I. INTRODUCTION

A muon collider requires the generation of intense short bunched positive and negative muon beams with a low emittance. These muon beams must be accelerated to their full collision energy before a significant percentage of the nuons decay into electrons or positrons (depending on the muon charge) and neutrinos. The full energy muon beams will be collided in a storage ring. The life of the muon beam in the collider ring is the time for the muon beam to make about 1000 turns around the ring.

In order for a muon collider to be feasible, large quantities of muons must be produced, then cooled to a low emittance. This report describes a magnetic capture system for charged pions produced by a production target. Once the pions are produced, they will decay into muons. The pions that are produced from the target must be kept bunched as they decay into muons in the first 40 meters downstream from the production target. The pion and muon bunching system uses phase rotation RF cavities to keep the pions and muons bunched. These cavities are combined with a system of solenoid magnets that keep the pion and muon captured.

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A typical muon production system for high energy physics experiments produces 10^{-5} muons for every incident proton on the production target. In order for the luminosity of the muon collider to be high enough the muon production rate has to be raised about five orders of magnitude. Even unconventional devices such as muon production horns are not efficient enough for the muon collider. (These devices are not efficient enough by at least two and a half orders of magnitude.) The production goal for muons used in for the muon collider is about 0.6 pions, from the target within the capture solenoid, for every incident proton that hits the production target at an energy of 16 GeV. By the time the pions have decayed to muons and enter the muon cooling system, there should be at least 0.3 muons per incident 16 GeV proton.

A muon production system that meets the requirements of the muon collider must have the following characteristics: 1) The number of positive and negative pion produced at the target must be maximized. This means that the target must be about two interaction lengths thick. 2) Pions that are produced must not be re-absorbed by the target. The design and the orientation of the target are critical. 3) Pions with large transverse momentum (large emittance) must be captured along with the pions with low transverse momentum (low emittance). 4) The spent protons must be separated from the pion beam. 5) The captured pions will have a range of momenta. The captured pion must be phase rotated in order to decay into a bunched muon beam before muon cooling can commence. 6) The beam power to the target is large (about 4 MW), in order for the correct number of muons to be produced. A large proton beam power means that the area around the target is subjected to large amount of beam heating and radioactivity. Less than one percent of the incident proton power end up in the muon beams that enter the cooling system. The rest of the beam power ends up in the spent proton beam dump and the solenoids near the production target.

I. THE TILTED PRODUCTION TARGET

High field solenoid with a large field volume around the target is proposed for the muon collider pion capture system. The capture solenoid must generate a magnetic induction of at least 20 T in a cylindrical space that is 500 mm long by about 150 mm in diameter. Tilting the pion production target has two effects: 1) The simulations suggest that pions produced on the tilted target are lass likely to be re-absorbed by the target. 2) The spent proton beam does not go down the pion decay and phase rotation channel if the tilt angle is large enough[4,5].

Calculations of pion yield from a target suggest that tilting the incident proton beam and target with respect to the solenoid axis will increase the pion yield for a given input proton intensity to the target. Pions produced in the upstream end of the target are not recaptured by the target downstream from the point where they were created. Simulations of pion production suggest that the pion production is maximized at a tilt angle of about 150 milliradians (see Figure 1). Above the 150 milliradian tilt angle the transverse momentum of some of the pions in the target becomes too high for capture to occur, so these pions are lost.

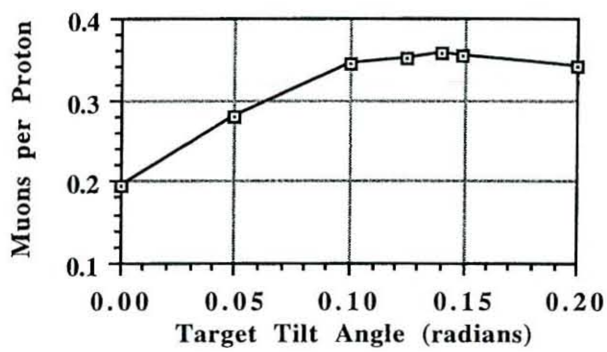

Fig. 1. Muon Production at the Cooling Channel Entrance for Optimized Targets as a Function of Target Tilt Angle

An increase in the yield of pions from the target means that the input beam power from the driver can be reduced, or muon production can be increased. Even with improved efficiency, a copper target will absorb about 230 kW of energy from the proton beam. Cooling the target is a difficult proposition, which will not be addressed here. Tilting the target and the input proton beam allows virtually all of the beam energy that has not been transferred to the captured pions to be absorbed in a beam dump. The design of the capture solenoid and the transition magnets into the phase rotation system will determine the location of the spent proton beam dump that may or may not be within the capture solenoid. Regardless of the location of the beam dump, the superconducting section of the capture solenoid system can not be allowed to absorb more than 500 W of the beam power from the beam. The target tilt angle may be greater than 0.15 radians (8.6 degrees) to allow for placement of the beam dump.

The pions are produced by a proton beam with a 1 nanosecond bunch length (0.3 m). As the pions move down the channel away from the target they tend to debunch with the low momentum pions going slower and the high momentum going faster. Phase rotation of the pion must start before the debunching has gone too far. The phase rotation channel must start within 3 to 5 meters of the target. The distance from the target where phase rotation starts is a function of the size of the beam dump near the target and the location of that beam dump. The induction in the solenoidal channel must be reduced from the capture value of 20 T to the solenoidal induction that will keep the pion beam captured within the phase rotation channel (an induction of 1 to 1.5 T). As they pion undergo phase rotation they decay to muons. The length of the phase rotation channel is about 50 meters.

III. THE PION CAPTURE SOLENOID SYSTEM

High field solenoid with a large field volume around a tilted target is proposed for the muon collider pion capture system. The capture solenoid must generate a magnetic induction of at least 20 T in a cylindrical space that is at least 500 mm long by about 150 mm in diameter. When the capture solenoid is 150 mm in diameter with an induction of 20 T one can capture pions with a transverse momentum as high 225 MeV/c[6]. Simulations show that a two interaction length tilted target will allow about 0.6 pions per incident proton to be captured in a 20 T solenoidal field that is 150 mm in diameter. The pion momentum spread ranges from about 100 MeV to above 1000 MeV. Most of the pions that can be bunched will have momenta in the range from 150 MeV to 700 MeV[4].

A capture solenoid that generates 20T must have a water cooled high Z liner (such as tungsten) about 60 mm thick, a water cooled solenoid insert coil, and a number of superconducting outsert coils that provide the background field for the water cooled insert solenoid. Two types of insert coils have been studied. The are: the water cooled Bitter solenoid and a conventional hollow conductor water cooled coil with ceramic insulation.

The Bitter type of coil is the most efficient per unit power for generating field Bitter solenoids can generate DC fields of over 30T when used alone. In the National High Magnetic Field Laboratory 45 T hybrid solenoid, about 30 T of the 45 T comes from a Bitter type insert coil[7]. A capture solenoid that uses a Bitter type insert solenoid can use that magnet to generate over half of the 20 T needed to capture the pions. As a result, the superconducting outsert solenoid can be made using only Nb-Ti coils at 1.8 K. A second advantage of a Bitter solenoid is the ability to vary the solenoid current density along its length to shape the magnetic field along the bore of the magnet. Another advantage of the Bitter solenoid is that the current density in a Bitter solenoid varies as the radius from the solenoid axis. The highest current densities occur closest to where the field is needed. This allows the magnetic stress to be more evenly spread around the coil. The most pressing problem with the Bitter solenoid is its short useful life. Most Bitter solenoids last only 500 to 2000 hours. In an application where the insert solenoid is subjected to a very radioactive environment, a short life time is not desirable. If the capture solenoid field were to be increased to 25 to 28 T, the used of a Bitter solenoid would have to be seriously considered. If the Bitter solenoid is to be used as an insert coil, considerable engineering design work is needed to extend the mean time to failure for the insert solenoid.

A conventional hollow conductor water cooled solenoid can have a very long life (80000 hours or more) provided a ceramic electrical insulation system is used. At best, the conventional solenoid can only be expected to provide 6 to 7 T of the 20 T induction needed to capture the pions. This means that the inner coils in the superconducting outsert magnet must be made from niobium tin. The baseline design for the capture solenoid calls for the use of a hollow conductor water cooled insert within a 14 to 15 T superconducting outsert solenoid system. The magnetic field on axis can be adjusted by adjusting the length and position of the water cooled coils and the superconducting coils.

The inside diameter of the water-cooled insert coil will be between 270 mm and 330 mm depending on the thickness of the water cooled radiation shield. Because of the intense radiation in the region, the conventional water cooled solenoid would have a ceramic insulation system. The high Z high density liner designed to absorb more than 99 percent of the energy from the particles produced by the target that are not captured by the magnetic field. The water cooled shield will act as a liner that will extend from the bore of the 20 T region to the throat of the first room temperature phase rotation RF cavity. The shield will protect the superconducting coil windings.

The superconducting coils must operate when there is a large radiation heating load (up to 500 W of heat due to particle showers in the superconducting coils). A cable in conduit design is suitable for the solenoids around the capture region. The superconducting coils will be graded with two niobium tin coils operating at inductions above 8 T and at least one niobium titanium coil operating below 8 T. The transition section of the pion capture solenoid can use niobium titanium superconducting coils. The superconducting outsert of the capture solenoid system can be cooled using superfluid helium at 1.8 K within the conduit. The 1.8 K cooling should be extended to the start of the phase rotation superconducting coils.

IV. PION AND MUON PHASE ROTATION SYSTEM

The field in the bore of the phase rotation RF cavities must be uniform. Simulation studies suggest that a field variation of up to three percent along the axis of the phase rotation channel may be acceptable. Various types of magnet designs were studied for the channel. The magnet designs were of two sorts: 1) 5 T superconducting magnet inside the cavities were studied. This option works only if the accelerating gaps in the cavities are small. The acceleration in the phase rotation section is unacceptable low for this option. 2) The cavities can be inside large bore superconducting magnets. This option allows for large cavity gaps and the field uniformity along the axis can have a variation that is less than one percent. The phase rotation system is based on a design that will have cavities inside of a series of large bore superconducting solenoids. Figure 2 illustrates possible locations and gap sizes for superconducting (S/C) coils located in and around the phase rotation RF cavities. Cases 1 and 2 are cases where the S/C coils are located inside the RF cavity. In case 1, the gap G between the S/C coils is 40 cm. In case 2, the gap between the S/C coils is reduced to 15 cm. Case 3 illustrates a case where the S/C coil is located on the outside of the RF cavity In case 3, the gap between the S/C coils is 40 cm (the same as case 1).

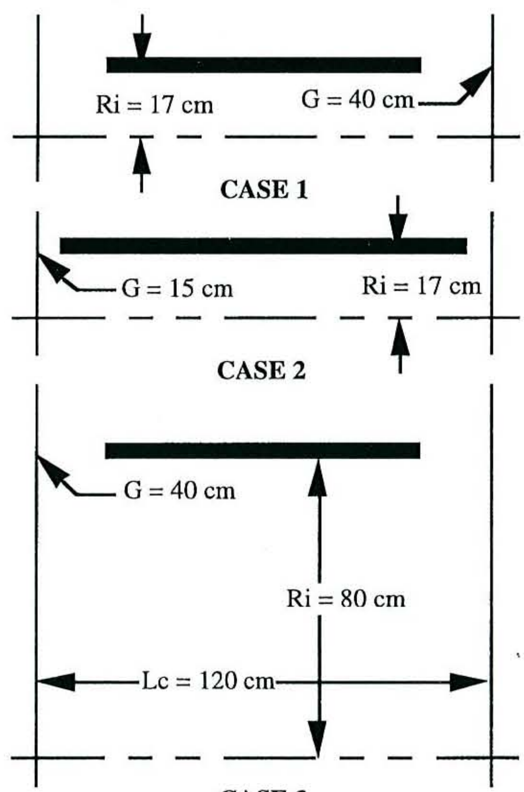

Fig. 2 Three cases for the location of the Phase Rotation Superconducting Coils in or around the RF Cavities

Table 1 A Comparison of Various Cases for Superconducting Magnets Inside and Outside the Phase Rotation RF Cavities

(L_{cell} = 120 cm, Ri = 17 cm, t_{coil} = 5 cm. Coil L = G*, RF Gap = G-4 cm)

CASE	Period Len Lc (cm)	RF Gap (cm)	Bmax (T)	Bmin (T)	Ratio	Bpeak (T)	Energy (MJ/m)
N = 1	120	56	8.607	1.462	5.035	8.99	1.75
CASE 1	120	36	6.520	2.324	2.800	7.24	1.35
N = 2	60	26	6.816	3.327	2.049	8.02	1.51
N = 3	40	16	5.821	4.318	1.348	7.50	1.38
CASE 2	120	11	5.276	4.381	1.200	5.82	1.14
N = 4	30	11	5.374	4.756	1.130	7.15	1.30
N = 5	24	8	5.194	4.935	1.052	6.89	1.23
N = 6	20	6	5.101	5.002	1.020	6.67	1.22
CASE 3**	120	36	5.103	4.986	1.023	5.31	21.2

* Except CASE 1, CASE 2 and CASE 3 (See Figure 2 for these cases.)

** This case has the coil outside of the cavity at a radius of 80 centimeters

Table 1 above compares various cases for S/C coils inside and outside of the RF cavities. Cases 1 and 2 and cases N = 1 through N = 6 have coils that have an inside radius Ri of 17 cm and a thickness of 5 cm. The period length Lc for cases N = 1 through N = 6 is 120 cm divided by N. In cases N = 1 through N = 6, the gap between the coils G is the same as the coil length, which is half the period length Lc. The RF gap for the cavity is assumed to be 4 cm shorter than the gap between the coils. B_{max} is the maximum induction on the solenoid axis, B_{min} is the minimum induction of the solenoid axis and B_{peak} is the peak magnetic induction in the S/C coils. Ratio is B_{max} over B_{min}. Energy is the stored energy per meter for an average channel induction of 5 T.

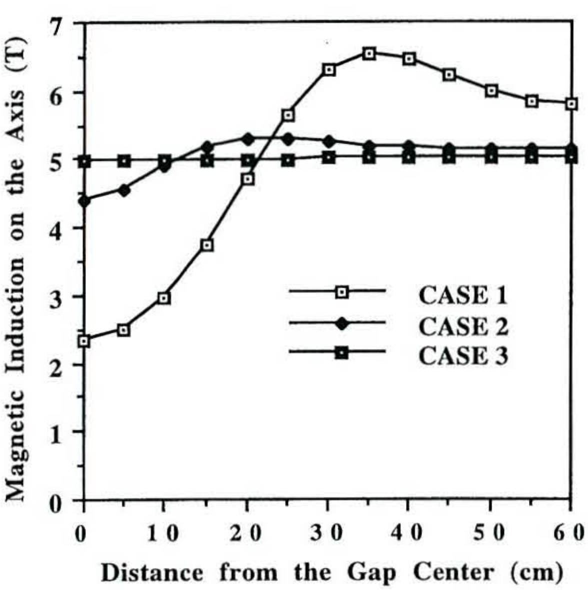

Fig. 3. Induction along the Axis of a 120 cm Long RF Cavity for Three Cases

Simulation studies over 40 to 60 meters of a solenoidal phase rotation channel show that the beam will remain captured provided the induction ratio on axis is below about 1.1. As the field becomes more uniform fewer pions and muons are lost during the phase rotation process. Table 1 and Figure 3 illustrate that if the gap between the superconducting coils is smaller than the about two thirds of the coil average radius, the magnetic field on axis will becomes uniform enough to permit particles to pass through the channel without loss. There are two approaches that one can use to produce an acceptably uniform field in the RF cavities. One can have a cavity periodicity that is about 1.3 times the S/C coil average radius or one can put the S/C coils around the RF cavities. When the S/C coils are located outside of the RF cavities a gap between the S/C coils is needed for the RF wave guides to feed the RF cavities. Figure 3 shows that putting the RF cavity inside of the superconducting magnet will always result in a uniform field on or around the solenoid axis where the pions and muons can be found. As a result, the phase rotation RF cavities will be entirely inside of the S/C coils.

The problem with having the solenoid coils outside of the RF cavities is the size of the cavities. The frequency of the cavities in the phase rotation system will vary from 50 MHz to 120 MHz. The low frequency cavities can be quite large (up to 3.5 meters in diameter for unfolded cavities operating at the lowest power consumption levels). Since the throat of these low frequency cavities must be quite large (up to 600 mm in diameter), the beam size can also be quite large. In order to reduce the cost of the superconducting solenoid around the RF cavities a design induction of 1.25 to 1.5 T has been selected for the phase rotation solenoids. One can optimize the cost of the phase rotation system by pitting the cost of the superconducting solenoids against the cost of the RF cavities, the RF cavity power supply tubes and the cost operation of the RF cavities.

Large bore (greater than 1.5 meters in diameter) low field (less than 2 T) superconducting solenoid can be built using the type of technology that is used to manufacture large bore detector solenoids[8]. Reliable stable phase rotation solenoids can be made using a copper based niobium titanium superconductor that is stabilized with very low resistance (at 4.5 K) ultra pure aluminum. A conductor suitable for this type of solenoid would be made using a conductor that is 1 part niobium titanium, 1 part copper and greater than 10 parts of RRR = 1000 ultra pure aluminum. Two layer coils can be wound inside of a hard aluminum shell that is cooled with two-phase helium in tubes mounted on the hard aluminum shell. The hard aluminum tube on the outside of the coil package provides support against the magnetic forces.

This type of superconducting coil is well within the current state of the art superconducting magnet technology. Aluminum stabilized superconductor can withstand a certain amount of beam heating without the coil quenching. The transition from a cable in conduit type of superconducting coil to an aluminum stabilized type of coil would have to occur downstream from the point where the target for the spent proton beam is located. The first stages of the phase rotation system may use a cable in conduit magnet to produce the magnetic field in the RF cavities The aluminum matrix superconducting phase rotation solenoids can be cooled using two-phase helium in tubes at 4.4 K.

V. TRANSITION BETWEEN THE PION CAPTURE AND THE PHASE ROTATION SYSTEM

The transfer solenoid system guides the magnetic field so that the magnetic induction decreases in an adiabatic way from 20 T to 1.25 T at the start of the phase rotation channel. A smooth transition of the magnetic induction can be achieved if the magnetic induction B(x) as a function of the distance from the end of the target x has the following relationship;

$$B(x) = \frac{Bo}{x + A} \qquad (1)$$

where Bo and A are fitting parameters. If one reduces the magnetic induction on axis adiabatically from 20 T to 1.25 T in 3 meters, Bo = 4 T m and A = 0.2 m. Once the magnetic induction has reached the design value for phase rotation or pion beam transport, the induction must remain constant.

It is interesting to note that the values of Bo and A will affect the design of the transition magnet system. Fast adiabatic changes in the induction on axis will result in lower values for Bo and A. In general, the lower the values of Bo and A, the higher the current density the superconducting coils must have in order for the field transition to be made. As a result, the use of cable in conduit coils may be precluded by having to reduce the induction on axis too quickly as one transitions from the capture solenoid to the phase rotation solenoid system. In general, the upper limit for cable in conduit coil overall current density is about 70 A mm. Superconducting coils that are potted can operate at current densities that are three times higher than cable in conduit coils. Further study will resolve the issue.

The inside radius of the beam pipe increases as the induction decreases. The minimum radius for the beam pipe r(x) at a distance x from the end of the target can be calculated using the following relationship;

$$r(x) = \sqrt{\frac{B(0)}{B(x)}}\, r(0) \qquad (2)$$

where r(0) is the radius of the beam pipe at the end of the target and B(0) is the magnetic induction at the end of the target. Equation 2 recognizes that transverse pion momentum has been transferred to forward pion momentum as the magnetic induction is decreased. In our case, the radius for pion capture around the target r(0) = 75 mm when B(0) = 20 T. A transfer of the captured pions from the 20 T target region to the 1.25 T phase rotation region requires an increase in the minimum beam pipe radius to 300 mm.

The final factor that affects the design of the transition coils is the location of the beam dump for the spent protons from the tilted target. If the proton can be dumped inside of the magnet, a relatively rapid transition can be made from the small aperture capture solenoid system to the large aperture phase rotation solenoid system. If the proton beam must be dumped outside of the phase rotation solenoid, the transition solenoid design becomes far more complex. Figure 4 shows a cross-section of a capture solenoid and transition solenoid system where the spent proton beam is dumped inside of the solenoid.

VI. CONCLUDING COMMENTS

Simulations show that large numbers of pions (greater than 0.3 pion per incident proton onto the tilted production target) can be captured by a 20 T solenoid that is 150 mm in diameter. The capture solenoid must be a hybrid magnet with both superconducting and water cooled copper windings. The captured pions can be moved to a 1.25 T phase rotation channel with very little loss. Once the pions are in the phase rotation channel, they will decay to muons that are bunched in momentum. This channel is made using large diameter superconducting solenoids that contain the phase rotation RF cavities. The phase rotation solenoids can be built using an aluminum matrix superconductor similar to the large detector magnets for high energy physics experiments.

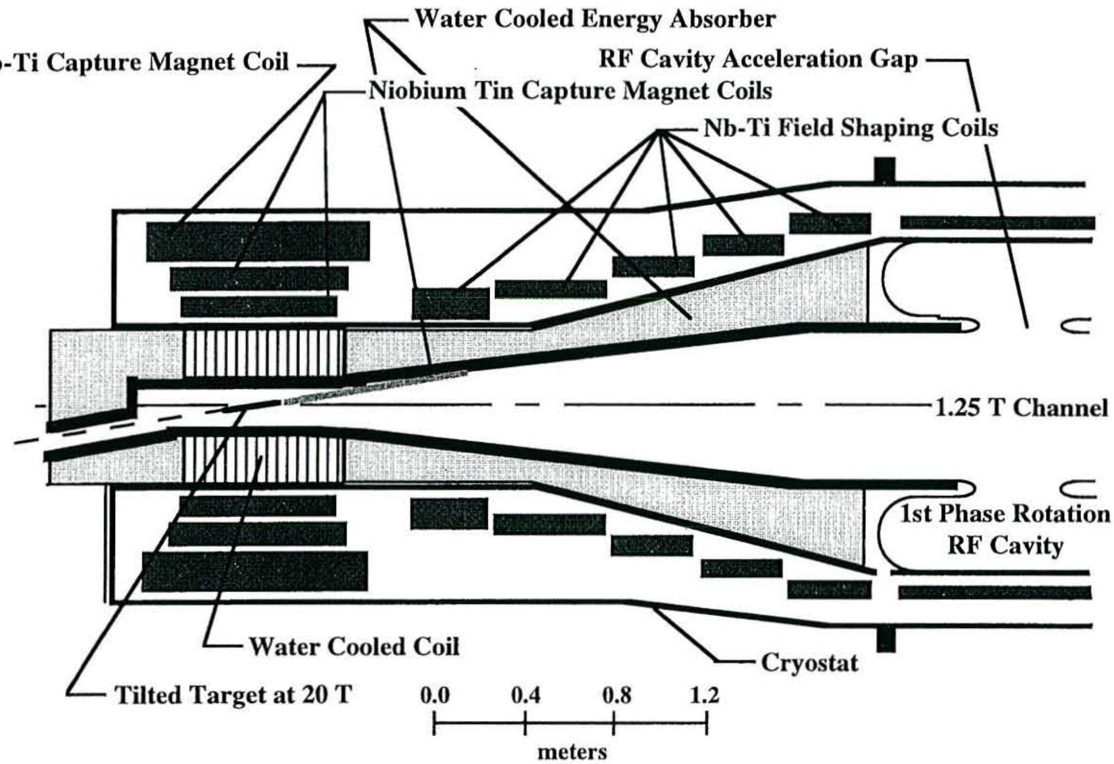

Fig. 4 A Cross-section View of the 20 T Hybrid Pion Capture Solenoid and the Transition Solenoids to a 1.25 T Phase Rotation RF Cavity Channel

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